ME 411 LAB 4: REMOTE SENSING LAND SURFACE TEMPERATURE

Prepared by
Katie Fankhauser
Luca Congeto
Evan Thomas

This is the first of a three part lab series for ME 411 Measurement and Instrumentation. In this sequence we will cover end-to-end data collection and analysis for a practical application. The overall objective is to develop an algorithm to determine ground surface temperature using satellite imagery, and to correlate and calibrate that algorithm against field measurements taken with calibrated thermocouples through a data acquisition system. At the end of the sequence, you will have an introductory familiarity with:

- Remote Sensing
- NASA's LandSat 8 satellite imagery products
- Geographic Information Systems (GIS) using a free software platform, QGIS
- Thermal infrared spectrum analysis
- Ground surface temperature derivation
- Thermocouple design and calibration
- Data acquisition through a analog to digital (A/D) converter
- MySQL data storage and retrieval
- Data calibration, statistical analysis and correlations using the R-Project for statistical computing
- Collecting field data for ground truthing
- Correlation and calibration of ground data against satellite derived data

Introduction

The term remote sensing usually describes the collection of data by satellites. In most cases, the "remote" refers to spectral imagery collected by cameras and other spectral instruments across a broad range of wavelengths. In case the of Earth observation, satellites take spectral data reflecting from the atmosphere and the Earth's surface. Interpretation of this data (often represented as imagery) requires an understanding of spectral data and physical properties of the Earth and atmosphere. It also often requires calibration against data collected on the Earth's surface or in the atmosphere directly – data from sensors that are in-situ, rather than "remote".

NASA's Earth Observatory website provides an excellent overview of the field of remote sensing, and the basic processes involved. Please carefully read this page:

http://earthobservatory.nasa.gov/Features/RemoteSensing/

The NASA / USGS LandSat program was launched in 1972 and was the first Earth observation satellite not designed for military use. The current satellite, LandSat 8, was launched in 2013. LandSat 8 has two main instruments, the Operational Land Imager (visible, near IR and short wave IR) and the Thermal Infrared Sensor (thermal IR). LandSat 8 covers every point on Earth every 16 days, and has a resolution of 15-100 meters.

TIRS was added to the LandSat 8 mission "when it became clear that state water resource managers rely on the highly accurate measurements of Earth's thermal energy obtained by LDCM's predecessors, Landsat 5 and Landsat 7, to track how land and water are being used. With nearly 80 percent of the fresh water in the Western U.S. being used to irrigate crops, TIRS will become an invaluable tool for managing water consumption."[1]

[1] http://www.nasa.gov/mission_pages/landsat/spacecraft/index.html#.VMaqKHDF-2E

In this lab, we will take LandSat 8 imagery from the TIRS spectroradiometer for Portland and derive ground surface temperature.

The USGS provides an introduction to processing LandSat 8 spectral data which we have quoted directly in the box below[2]:

Using the USGS Landsat 8 Product

The standard Landsat 8 products provided by the USGS EROS Center consist of quantized and calibrated scaled Digital Numbers (DN) representing multispectral image data acquired by both the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS).

The products are delivered in 16-bit unsigned integer format and can be rescaled to the Top Of Atmosphere (TOA) reflectance and/or radiance using radiometric rescaling coefficients provided in the product metadata file (MTL file), as briefly described below. The MTL file also contains the thermal constants needed to convert TIRS data to the at-satellite brightness temperature. Further details can be found in the LDCM Cal/Val Algorithm Description Document and the Landsat 8 Science Users' Handbook available from the Landsat website.

Conversion to TOA Radiance
OLI and TIRS band data can be converted to TOA spectral radiance using the radiance rescaling factors provided in the metadata file:

$$L_\lambda = M_L Q_{cal} + A_L$$

where:

L_λ = TOA spectral radiance (Watts/(m2 * srad * µm))
M_L = Band-specific multiplicative rescaling factor from the metadata (RADIANCE_MULT_BAND_x, where x is the band number)
A_L = Band-specific additive rescaling factor from the metadata (RADIANCE_ADD_BAND_x, where x is the band number)
Q_{cal} = Quantized and calibrated standard product pixel values (DN)

Conversion to TOA Reflectance
OLI band data can also be converted to TOA planetary reflectance using reflectance rescaling coefficients provided in the product metadata file (MTL file). The following equation is used to convert DN values to TOA reflectance for OLI data as follows:

$$\rho\lambda' = M_\rho Q_{cal} + A_\rho$$

where:

$\rho\lambda'$ = TOA planetary reflectance, without correction for solar angle. Note that $\rho\lambda'$ does not contain a correction for the sun angle.
M_ρ = Band-specific multiplicative rescaling factor from the metadata (REFLECTANCE_MULT_BAND_x,

[2] https://landsat.usgs.gov/Landsat8_Using_Product.php

where x is the band number)
A_ρ = Band-specific additive rescaling factor from the metadata (REFLECTANCE_ADD_BAND_x, where x is the band number)
Q_{cal} = Quantized and calibrated standard product pixel values (DN)

TOA reflectance with a correction for the sun angle is then:

$$\rho\lambda = \frac{\rho\lambda'}{\cos(\vartheta_{SZ})} = \frac{\rho\lambda'}{\sin(\vartheta_{SE})}$$

where:

$\rho\lambda$ = TOA planetary reflectance
ϑ_{SE} = Local sun elevation angle. The scene center sun elevation angle in degrees is provided in the metadata (SUN_ELEVATION).
ϑ_{SZ} = Local solar zenith angle; $\vartheta_{SZ} = 90° - \vartheta_{SE}$

For more accurate reflectance calculations, per pixel solar angles could be used instead of the scene center solar angle, but per pixel solar zenith angles are not currently provided with the Landsat 8 products.

Conversion to At-Satellite Brightness Temperature
TIRS band data can be converted from spectral radiance to brightness temperature using the thermal constants provided in the metadata file:

$$T = \frac{K_2}{ln\left(\frac{K_1}{L_\lambda} + 1\right)}$$

where:

T = At-satellite brightness temperature (K)
L_λ = TOA spectral radiance (Watts/(m2 * srad * µm))
K_1 = Band-specific thermal conversion constant from the metadata (K1_CONSTANT_BAND_x, where x is the band number, 10 or 11)
K_2 = Band-specific thermal conversion constant from the metadata (K2_CONSTANT_BAND_x, where x is the band number, 10 or 11)

Based on these formulas, we will be able to concert digital numbers to At-Satellite Brightness Temperature. For Landsat 8, the *K1* and *K2* values are provided in the image metafile.

There are several studies about the calculation of land surface temperature. For instance, using NDVI for

the estimation of land surface emissivity[3], or using a land cover classification for the definition of the land surface emissivity of each class[4].

For instance, the emissivity (*e*) values of various land cover types are provided in the following table[5]:

Land surface	**Emissivity *e***
Soil	0.928
Grass	0.982
Asphalt	0.942
Concrete	0.937

Therefore, the land surface temperature can be calculated as:

$$T_s = T_B / [\ 1 + (\lambda * T_B / p)\ ln(e)\ ]$$

where:

- λ = wavelength of emitted radiance
- $p = h * c / s$ (1.438 * 10^-2 m K)
- h = Planck's constant (6.626 * 10^-34 Js)
- s = Boltzmann constant (1.38 * 10^-23 J/K)
- c = velocity of light (2.998 * 10^8 m/s)

The values of λ for the thermal bands of Landsat 8 are listed in the following table:

Satellite	**Band**	**Center wavelength (μm)**
Landsat 8	10	10.8
Landsat 8	11	12

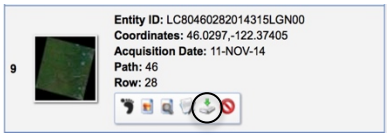
[3] Sobrino, J.; Jiménez-Muñoz, J. C. & Paolini, L. 2004. Land surface temperature retrieval from LANDSAT TM 5 Remote Sensing of Environment, Elsevier, 90, 434-440

[4] Weng, Q.; Lu, D. & Schubring, J. 2004. Estimation of land surface temperature–vegetation abundance relationship for urban heat island studies. Remote Sensing of Environment, Elsevier Science Inc., Box 882 New York NY 10159 USA, 89, 467-483

[5] Mallick, J.; Singh, C. K.; Shashtri, S.; Rahman, A. & Mukherjee, S. 2012. Land surface emissivity retrieval based on moisture index from LANDSAT TM satellite data over heterogeneous surfaces of Delhi city International Journal of Applied Earth Observation and Geoinformation,, 19, 348 - 358

Download Software and Data Products

1. You will need to install the mapping software, QGIS (with the GDAL package), as well as the python modules, Numpy, Scipy, and Matplotlib.
    a. For Windows all needed software can be found here: http://www.qgis.org/en/site/forusers/download.html
    b. For Mac, install QGIS and GDAL here: http://www.kyngchaos.com/software/qgis and the modules here: http://www.kyngchaos.com/software/python
    c. Note: Some of the steps contained in this tutorial require a significant amount of space on your hard drive. Before beginning, you should make sure you have at least 30 GB or more of free space.
2. The Landsat8 images can be downloaded from http://earthexplorer.usgs.gov
    a. Enter Portland, OR as the "Address/Place"; clicking the result will populate the coordinates for you.
    b. Go to the "Data Sets" tab. Expand "Landsat Archive" and check "L8 OLI/TIRS". Good review: http://pubs.usgs.gov/fs/2013/3060/pdf/fs2013-3060.pdf.
    c. Press "Results" and find the image from November 11, 2014. You can preview the image and its attributes by clicking on the image icon.
    d. Choose the download icon and download the "Level 1 GeoTIFF Data Product" (you will need to create an account and login before you can do this – it's easy, quick, and free).

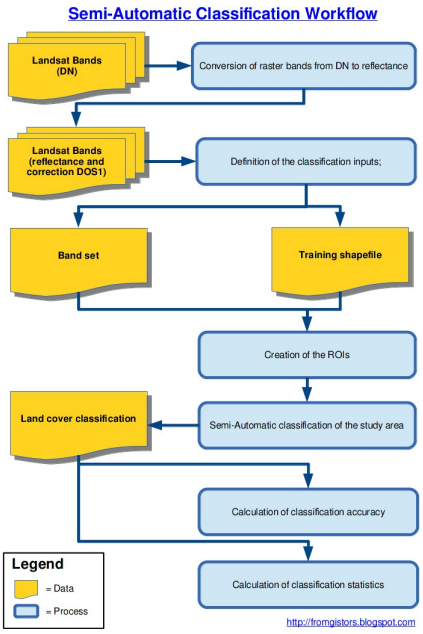


    e. Once the package has completed downloading, move it to a file on your computer that is easy to access. You may need to download an external Archive Utility to unzip the file.
3. Now you're ready to start mapping!

GIS Data Processing

1. GIS Basics
    a. In order to get a good introduction to Geographic Information Systems (GIS)—what they can do and how they work, read these pages:
        i. Introducing GIS, Vector Data, Raster Data, and Coordinate Reference Systems. All can be found at: http://docs.qgis.org/2.6/en/docs/gentle_gis_introduction/introducing_gis.html
        ii. The user manual created by QGIS authors is also a valuable tool if you decide to continue using QGIS applications: http://docs.qgis.org/2.6/en/docs/training_manual/
2. In this tutorial, we will estimate the land surface temperature over Portland, OR using Landsat8 imagery and the *Semi-Automatic Classification Plugin (SCP)* for QGIS. There are four phases we will go through:
    a. Conversion of raster bands from digital numbers (DN) to reflectance and At Satellite Temperature
    b. Land cover classification of study area
    c. Reclassification of the land cover classification to emissivity values
    d. Conversion from At Surface Temperature to Land Surface Temperature

3. In the Landsat package you downloaded from USGS, we will use bands 2 – 7, and 10. The other bands we will not use are designated for coastal aerosol, panchromatic, and high cloud cover. Visit http://landsat.gsfc.nasa.gov/?page_id=5377 for a review of the bands collected by Landsat8. The following is a list of the bands we will use and their respective spectrum.
    a. Band 2 – Blue
    b. Band 3 – Green
    c. Band 4 – Red
    d. Band 5 – Near-Infrared
    e. Band 6 – Short Wavelength Infrared 1
    f. Band 7 – Short Wavelength Infrared 2
    g. Band 10 – Thermal band (TIRS) 1 (Note: band 11 is also a thermal band, but there is larger uncertainty in its values)
    h. Make sure the metadata file (MTL.txt) remains with the dataset.



4. Installing the SCP Plugin
    a. Open QGIS
    b. In the menu bar, choose “Plugins”, then “Manage and Install Plugins”
    c. Search for Semi-Automatic Classification Plugin and click “Install plugin”
    d. Close and open QGIS again to restart the plugin application.
    e. View > Panels > SCP: ROI Creation. Do the same for SCP: Classification. Layers and Toolbox should also be checked if they aren’t already.

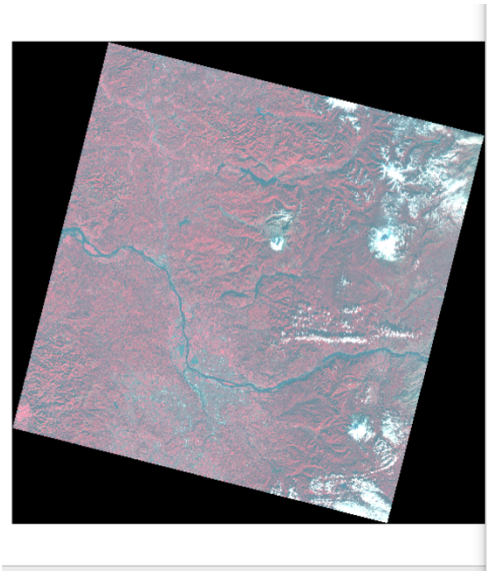
I. CONVERSION OF RASTER BANDS FROM DN (“DIGITAL NUMBERS”) TO REFLECTANCE

The SCP automatically converts Landsat Digital Numbers (DN)—dimensionless pixel values—to Top of Atmosphere reflectance (TOA), which is defined as the ratio between the radiation striking a surface and the radiation reflected off of the surface. In the same step, the SCP performs atmospheric correction using the DOS1 (Dark Object Subtraction 1 (DOS1) method. Conversion and correction are necessary because atmospheric effects, such as absorption and scattering, affect the electromagnetic energy measured by satellites.

1. From the SCP toolbar select the “Preprocessing” icon and then the “Landsat” tab.

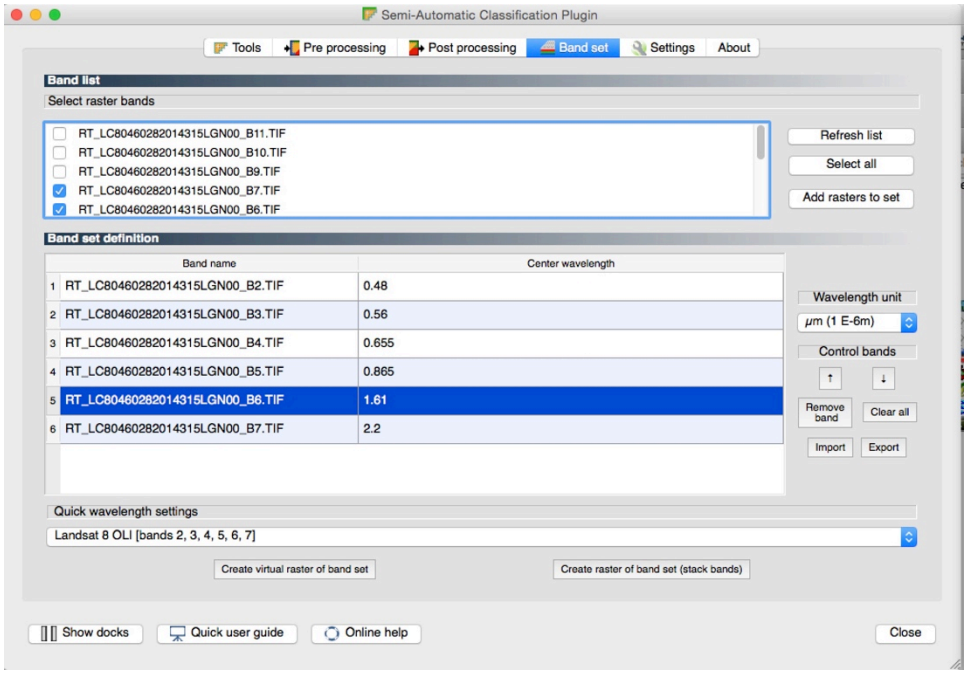
2. Select directory where you saved the Landsat bands and metafile. For the output directory, save the converted bands to a new folder.
3. Check the box next to “Apply DOS1 atmospheric correction” and leave checked “Create Virtual Raster”, which we will use to create a red, blue, green color composite.
4. Perform conversion. This may take up to several minutes. When it is complete the converted bands and the virtual raster landsat.vrt are loaded into the Layers panel.

5. To create an rgb color composite, double-click on “landsat” and navigate to the “Style” tab. Set Band 5 as the red bed, Band 4 as the green band, and Band 3 as the blue band. This false color combination is best for viewing vegetation because healthy vegetation reflects near-infrared wavelengths.
6. Make sure “Contrast enhancement” is selected as “Stretch to MinMax” and then press “Load” in the right hand box to redefine the min and max values of the bands you selected in the previous step. Your map should look like similar to the one to the right.

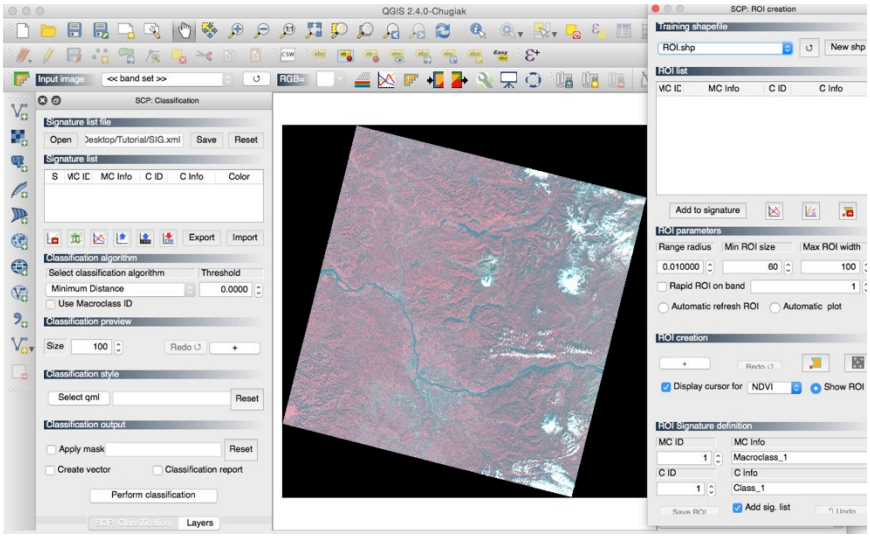


7. Select the “Band Set” icon from the SCP toolbar.

8. Select bands 2 -7 (do not select any bands outside of this range) and “Add rasters to set.” The SCP will average the value of spectral signatures in each band to create the land cover classification so we do not want to include bands that are outside of our spectrum of interest. Reorder the bands so that they are in increasing order (i.e. B2 will be in the first spot and B10 will be in the last spot). From the dropdown Quick wavelength settings menu select “Landsat 8 OLI.” The center wavelength of your bands should have now been adjusted. Your screen should match the one below.



9. In the SCP: ROI creation panel, save a new shapefile where the Regions of Interest in the following step will be stored. Click the button “New shp” and select where to save the shapefile (for instance ROI.shp)
10. Create a signature list file where the spectral signatures of the land cover classes will be stored and used to create the classification by clicking the button “Save” in the SCP: Classification panel (for example SIG.xml).
11. In the SCP toolbar, the name << band set >> is displayed in the Input image combo box. The shapefile name is displayed in the Training shapefile combo box, and the path to the xml file is displayed in the Signature list file. See below.



12. It is also a good idea to save the entire project at this time. Go to Project in the top menu bar and “Save as.” Choose a file where to save your work. Remember to frequently save your project throughout this tutorial—some of the processing can cause QGIS to crash or freeze at times.

II. COLLECTION OF ROIS AND SPECTRAL SIGNATURES

Regions of Interest (ROIs) are polygons drawn over homogeneous areas of the image that represent land cover classes. ROIs can be drawn manually or with a region growing process (i.e. image segmentation that groups similar pixels), and they should account for the spectral variability of land cover classes.

The Semi-Automatic Classification Plugin (SCP) calculates the **spectral signatures** (which are used by classification algorithms) considering the pixel values under each ROI.

SCP allows for the definition of a **Macroclass ID** (i.e. MC ID) and a **Class ID** (i.e. C ID) for each ROI or spectral signature, which are the identification codes of land cover classes.

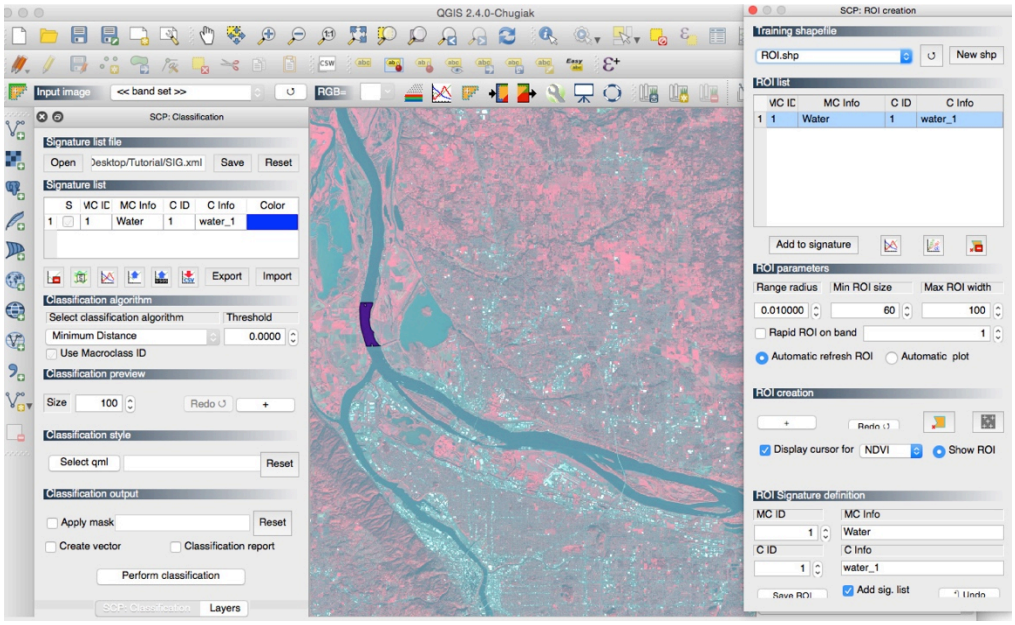
Macroclasses allows for the classification of materials that have different spectral signatures (therefore are processed individually), but belong to the same land cover class (thus the same MC ID is assigned to these pixels). For instance we could classify grass (e.g. MC ID = 1 and C ID = 1) and trees (e.g. MC ID = 1 and C ID = 2) as a vegetation macroclass (e.g. MC ID = 1).

Every ROI (or spectral signature) should have a unique C ID, while the MC ID can be shared with other ROIs. In the dock Classification it is possible to choose between MC ID and C ID classification.”

1. In order to create an ROI, choose the + next to “Create a ROI” on the SCP: ROI Creation panel. You may choose whether to leave the NDVI or EVI, measures of vegetation that are respectively either chlorophyll sensitive or based on variations in canopy, cursor on as you navigate the map. Zoom in the map and click on a blue pixel of the Willamette River. After a few seconds, a semitransparent polygon will appear over your selection. Under the “ROI parameters” heading,

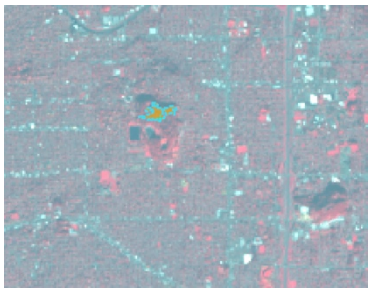
check the “Automatic Refresh ROI” button and experiment changing the “Min ROI size” and “Range radius” to see its effect on the ROI selection.

2. Assign a Macroclass ID and Class ID to the selection and write a brief description of the ROI under “ROI Signature definition.” Make sure each land cover class (i.e. water) is assigned the same Macroclass ID and that each ROI within this class is given a sequential Class ID
3. In order to save the ROI to the training shapefile, click the button “Save ROI to shapefile” making sure the box next to this button, “Add sig. list” is checked. The ROI is now saved in the “ROI list” and the spectral signature is added to the “Signature list” table. Define the color of classes that will be used in the classification by double clicking on the “Color” column in the “Signature list” of the SCP: Classification panel (i.e. use blue for water).

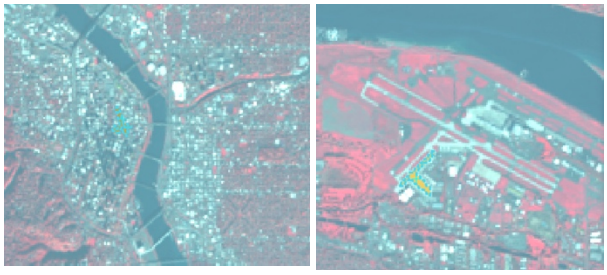


4. Create multiple ROIs for the remaining land cover classes: vegetation, builtup, bare soil, and snow. Remember to assign a new incremental class ID to each ROI and a different macroclass ID (MC ID) to each unique land cover class. Creation of around ten ROIs would give you a good start, but you should define as many as needed for a classification that both correctly and completely assigns land cover classes. Here are some examples:

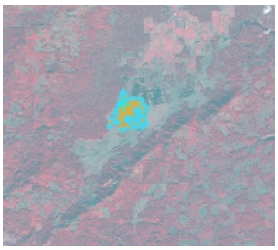
Vegetation (MC ID 2):



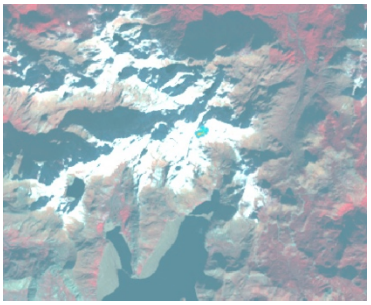
Builtup (MC ID 3):



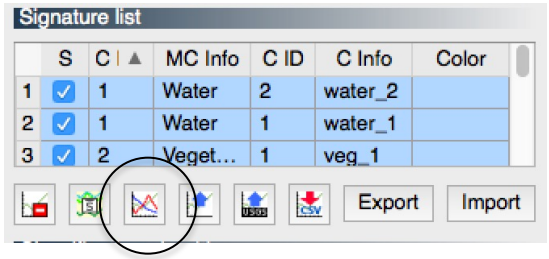
Bare soil (MC ID 4):

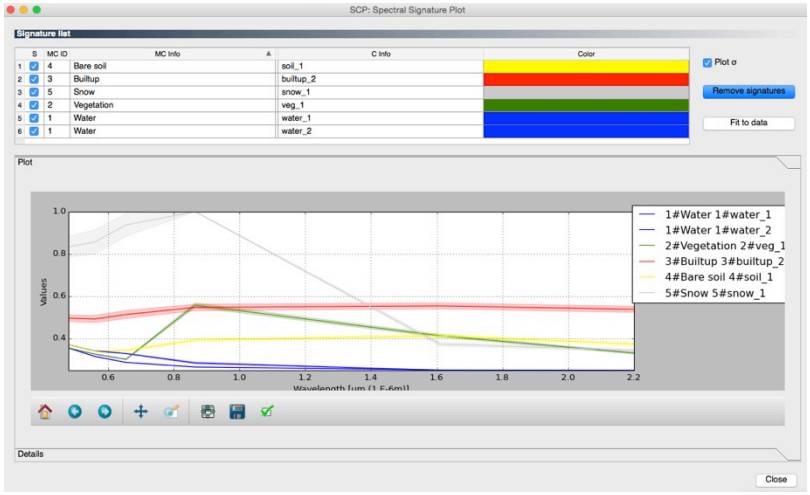


Snow (MD ID 5):

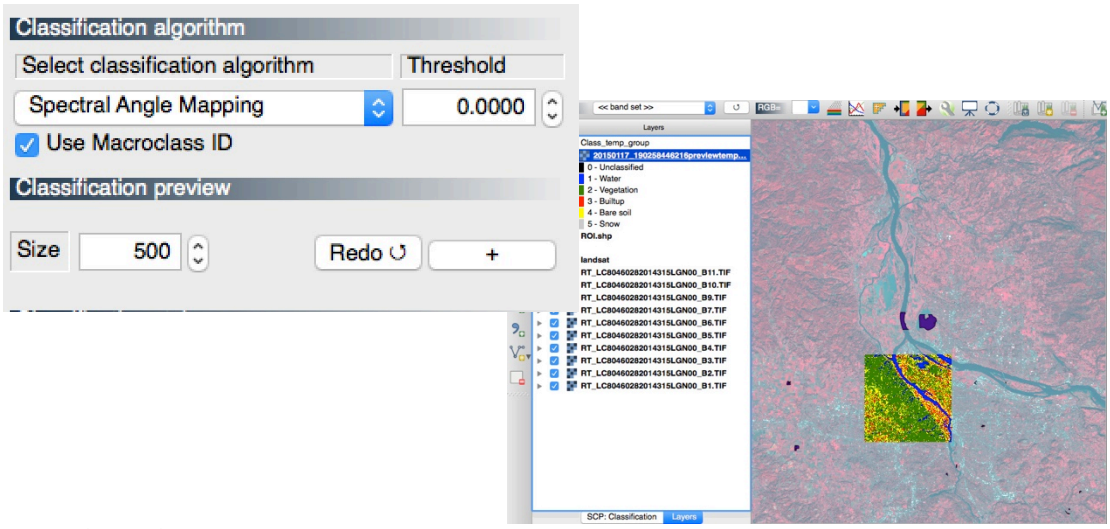


5. As you are working, compare the spectral signatures of each ROI you collect in order to evaluate the spectral similarity. In the "Signature list" table highlight one or more of the signatures and click the button that pulls up the spectral signature plot. By checking the box "Plot σ", the standard deviation of each signature is displayed.

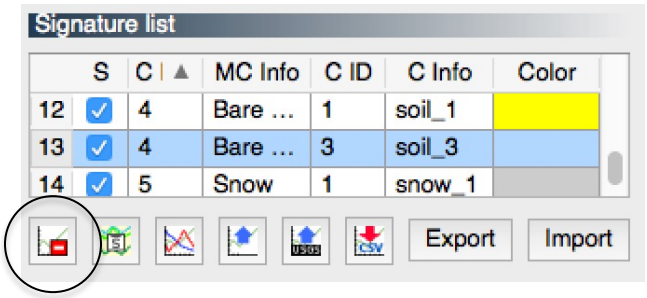




6. Another way to check the accuracy of your creation of signatures is to perform a temporary classification on part of the image. Select "Spectral Angle Mapping" as the classification algorithm in the SCP: Classification panel; make sure "Use Macroclass ID" is checked; increase the "Size" to 500 (the size of the classification preview in pixel unit); choose the + button on the right hand side of the "Classification preview" box; then click on any area of your map. A small preview of the classification output will appear and you can compare it to the type of land cover evident in your base raster layer.



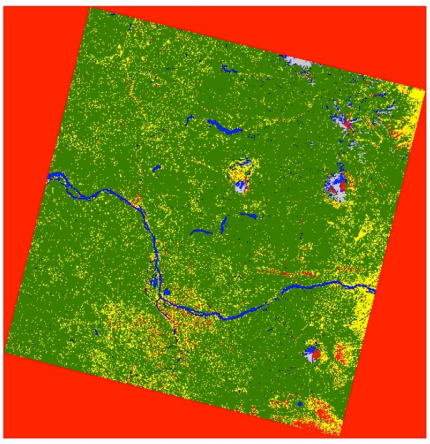
7. If any of the signatures appear inaccurate—too similar to another land class or not similar enough to its own land class—you can delete them by highlighting them in "Signature list" and using the remove icon.



8. When you are satisfied that you have produced a good classification by visually comparing the preview to the rgb image, classification of the entire image can be completed. Otherwise, you should remove spectral signatures and/or add new spectral signatures by creating other ROIs.

END OF IN LAB WORK – HAVE YOUR LAB TA CHECK THAT YOU HAVE PERFORMED THE CLASSIFICATION PREVIEW.

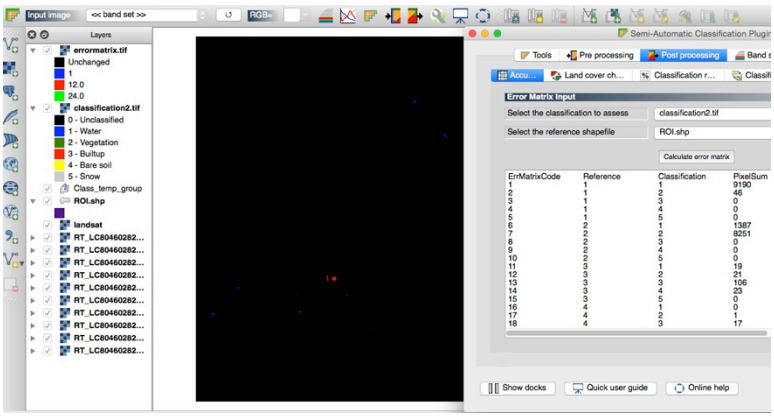
9. In the "Classification output" dock, press the "Perform classification" button and save the output (ex. classification.tif). The classification will take several minutes to complete so wait until it has finished "executing" and has been loaded into the Layers panel. It should look similar to the below image.



Note: Some inconsistencies will remain in your result. For example, take a look at the lower right hand corner where there is some cloud cover in the original image. The classification is now reading the cloud and its shadows as built-up and bare soil. Estimating land surface temperature from satellite data will never be perfect, hence the need for ground truthing measurements.

10. You can further check the accuracy of your land cover classification by performing an accuracy assessment between the classification and the training ROIs. Select Post Processing > Accuracy from the SCP toolbar.

11. Select your classification.tif layer as the "classification to assess" and the ROI.shp as the "reference shapefile." If these do not appear in the dropdown menus "Refresh list" and check again. Press the "Calculate error matrix" button and select where the error matrix (a .csv file) and the error raster are saved. The error matrix will be displayed in the SCP screen, and saved in the error matrix .csv file, and the error raster will be loaded in QGIS. Each value, or color, represents the comparison between the user created ROIs and the classification produced by the SCP.



12. Scrolling to the bottom of the Error Matrix window shows the accuracy of the classification.

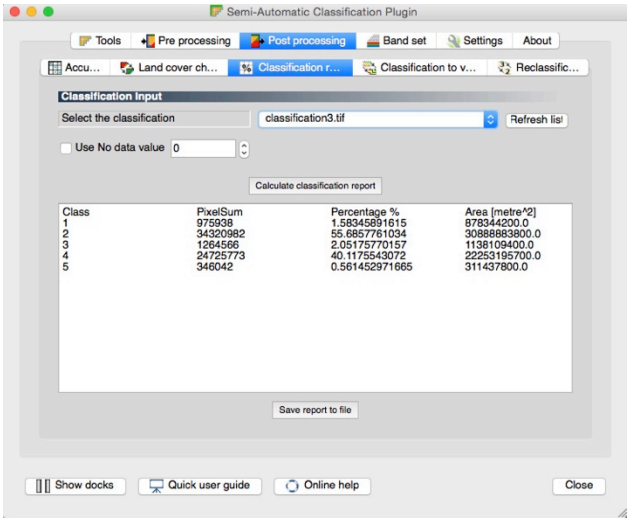
ERROR MATRIX

	> Reference			
V Classification	1	2	3	4
1	9190	1387	19	0
2	46	8251	21	1
3	0	0	106	17
4	0	0	23	587
5	0	0	0	0
Total	9236	9638	169	605

Overall accuracy [%] = 92.3166708957
Class 1 producer accuracy [%] = 99.5019488956 user accuracy [%] = 86.7308418271
Class 2 producer accuracy [%] = 85.6090475202 user accuracy [%] = 99.1825940618
Class 3 producer accuracy [%] = 62.7218934911 user accuracy [%] = 86.1788617886
Class 4 producer accuracy [%] = 97.0247933884 user accuracy [%] = 96.2295081967
Class 5 producer accuracy [%] = 100.0 user accuracy [%] = 100.0

In this classification, the overall accuracy is around 92%. In general, classification accuracy > 80% is considered good. It is also useful to consider the error for single classes. In the upper half of the image above, the number of pixels classified correctly is displayed along the major diagonal. As you can see the largest errors are in class 3 (bare soil). This is also confirmed by a comparison of user and producer accuracy. In order to improve the results, one would want to collect more ROIs and spectral signatures in the bare soil class, paying attention to the spectral similarity with other classes.

13. We can also use the SCP tool to calculate the percentage and area of land cover classes. While you are still in the "Post Processing" window select the "Classification report" tab. Select the classification.tif and press "Calculate classification report." After a few seconds the report will generate the percentage and area (the area unit is calculated from the image itself) of each land cover class in the image. In this example, vegetation comprises about 56% of the total image while being around 30,000 square kilometers in size.



Note: These figures were created for the purpose of this tutorial. Several more ROIs of each class and consideration of their spectral variability are needed for a better classification. Also, field data is useful for improving the creation of ROIs and spectral signatures.

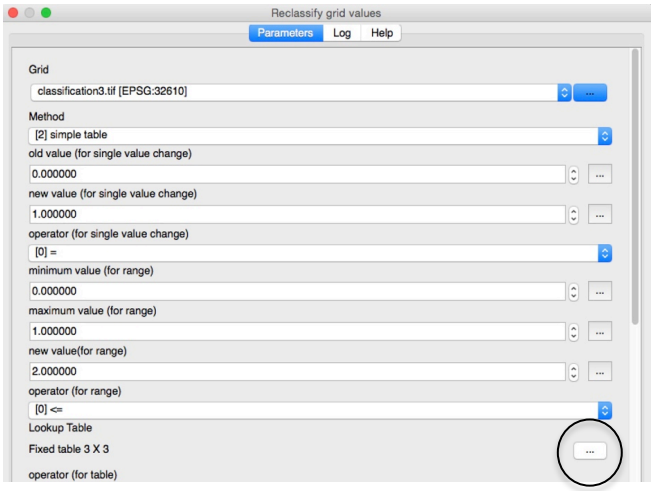
III. RECLASSIFICATION OF THE LAND COVER CLASSIFICATION TO EMISSIVITY VALUES

1. The emissivity (*e*) values for the land cover classes are provided in the following table (these values are only indicative because they should be obtained from field survey).

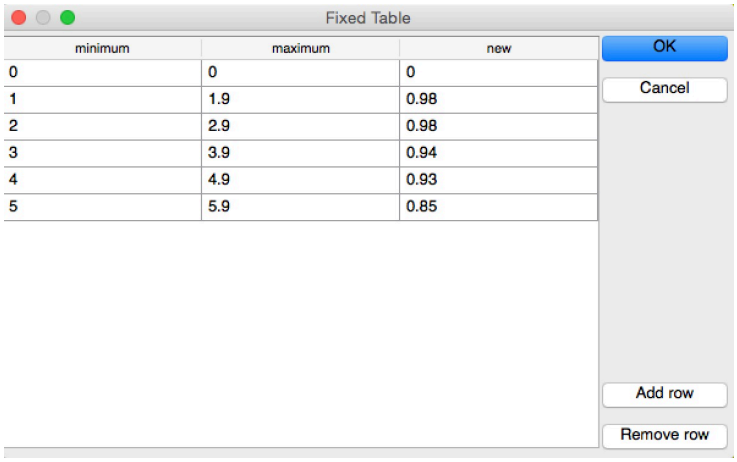
Land Surface	**Emissivity *e***
Water	0.98
Vegetation	0.98
Builtup	0.94
Bare soil	0.93
Snow	0.85

http://www.infrared-thermography.com/material-1.htm

2. In the "Processing Toolbox" panel navigate to SAGA > Grid – Tools > "Reclassify grid values." In this tool window, select your "classification.tif" as the "Grid"; under method choose "[2] simple table"; and press the "…" button to the right of the "Fixed table 3 X 3" heading."

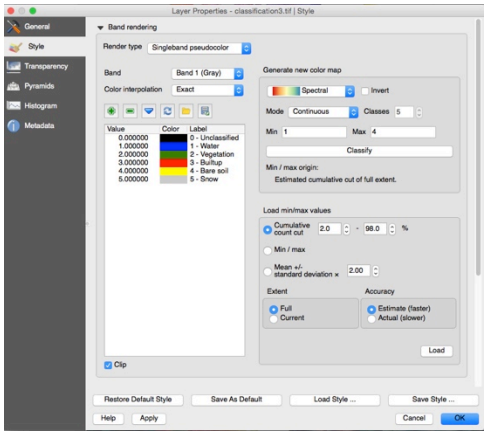


3. This button will bring up a table with Minimum, Maximum (the range of the current value), and New (value) columns. The minimum and maximum values are based on the Macroclass ID you assigned to each land cover class in previous steps. For example, water (MC ID 1) will have a minimum value of 1, maximum value of 1.9, and a new value of 0.98 (*e*). Fill out the table as seen below, making sure to leave the first line as "unclassified."

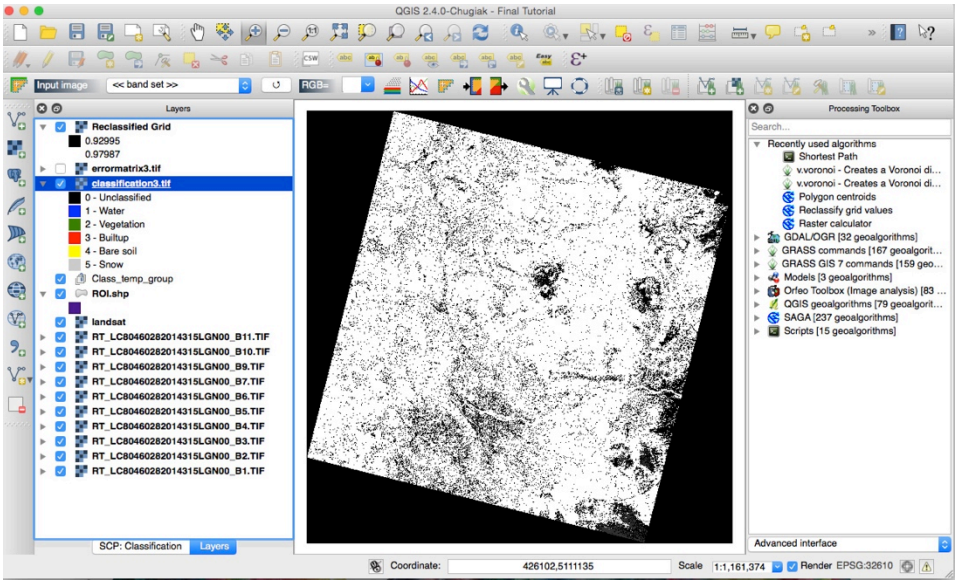


minimum	maximum	new
0	0	0
1	1.9	0.98
2	2.9	0.98
3	3.9	0.94
4	4.9	0.93
5	5.9	0.85

Note: The value of each land cover class can be confirmed by double clicking the classification raster in the "Layers" panel to bring up the Properties > Style window. This is also where you can change the colors and labels of the classes.

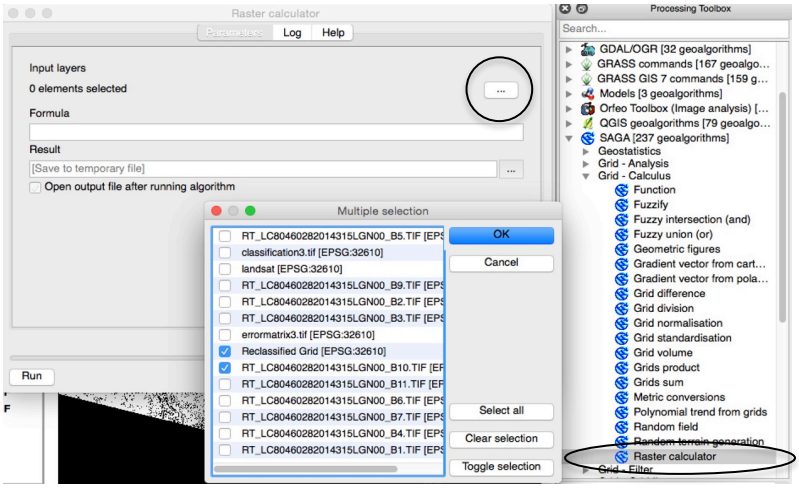


4. Select where to save the emissivity raster (by clicking the "…" button under the "Reclassified Grid" heading. Press "Run" and after a few moments the reclassified grid (i.e. emissivity) will be added into QGIS.



IV. CONVERSION FROM AT SATELLITE TEMPERATURE TO LAND SURFACE TEMPERATURE

1. Now we will convert the At-Satellite Brightness Temperature (calculated Step III) to Land Surface Temperature.
2. From the "Processing toolbox" panel navigate to SAGA > Grid – Calculus > "Raster calculator." Press the "…" button to choose the two input layers: the emissivity raster ("Reclassified grid") and the thermal Landsat8 band ("B10").



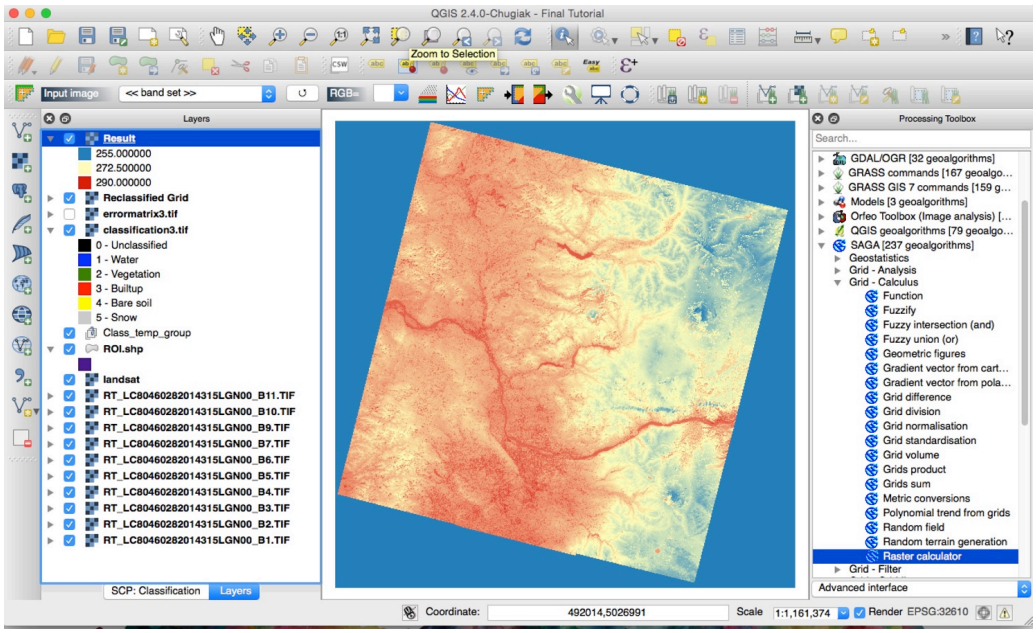
3. Under formula write:

$$b / (1 + (10.8 * b / 14380) * \ln(a))$$

where a is the emissivity raster and b is the brightness temperature raster.

NOTE: If the B10 band appears above the reclassified grid during selection, you must adjust the formula to match this ordering [i.e. *a / (1 + (10.8 * a / 14380) * ln(b))*]

4. Choose where to save the result (i.e.landsurfacetemp.tif) and press “Run.” After a few seconds, the land surface temperature raster (in kelvin) will be loaded in QGIS. In order to make the image more visually meaningful you must specify the style of the image.
5. Double click on the “Result” layer; this should bring up the “Properties > Style” window. As Render type choose “Singleband pseudocolor.” Under the “Generate new color map” box keep “Spectral” as the color scheme, but check to “Invert” it; the mode to use is “Equal Interval” with 3 “Classes. The “Min” and “Max” values can be estimated by looking at the Raster Histogram found under the “Histogram” tab on the sidebar. Finally, back in the “Style” tab, press the button “Classify.” Press “OK” to apply the results and get back to the main window.
6. Congratulations, you now have a working image of land surface temperature over Portland on November 11, 2014!



NOTE: Keep in mind that analysis of satellite imagery is best used for relative, not exact, measurements. Thus, it is important to perform field surveys to determine actual land cover classification of the area and measure surface emissivities when possible.

Homework 5 Assignment

Email fankhauk@onid.oregonstate.edu your error matrix csv file and a screen shot of your final image in QGIS as above by February 10 at 10 am.